Algorithm Theoretical Basis Document (ATBD) for the Conical-Scanning Microwave Imager/Sounder (CMIS) Environmental Data Records (EDRs)

Volume 6: Pressure Profile EDR

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Title		Covering
ATBD for the CMIS TDR/SDR Algorithms		
ATBD for the CMIS EDRs	Volume 1: Overview	Part 1: Integration
		Part 2: Spatial Data Processing • Footprint Matching and Interpolation • Gridding • Imagery EDR
	Volume 2: Core Physical Inversion Module	
	Volume 3: Water Vapor EDRs	Atmospheric Vertical Moisture Profile EDR Precipitable Water EDR
	Volume 4: Atmospheric Vertical Temperature Profile EDR	
	Volume 5: Precipitation Type and Rate EDR	
	Volume 6: Pressure Profile EDR	
	Volume 7: Cloud EDRs	Part 1: Cloud Ice Water Path EDR
		Part 2: Cloud Liquid Water EDR
		Part 3: Cloud Base Height EDR
	Volume 8: Total Water Content EDR	
	Volume 9: Soil Moisture EDR	
	Volume 10: Snow Cover/Depth EDR	
	Volume 11: Vegetation/Surface Type EDR	
	Volume 12: Ice EDRs	Sea Ice Age and Sea Ice Edge Motion EDR Fresh Water Ice EDR
	Volume 13: Surface Temperature EDRs	Land Surface Temperature EDR Ice Surface Temperature EDR
	Volume 14: Ocean EDR Algorithm Suite	Sea Surface Temperature EDR Sea Surface Wind Speed/Direction EDR Surface Wind Stress EDR
	Volume 15: Test and Validation	All EDRs

Bold = this document

TABLE OF CONTENTS FOR VOLUME 6

LIST OF TABLES

LIST OF FIGURES

1. Abstract

2. Introduction

2.1. Purpose

The purpose of this document is to provide a reference for the background, methodology, and performance of the CMIS Pressure Profile EDR algorithm. It presents the theoretical basis for retrieving pressure profiles from conically-scanning microwave satellite observations, a description of the algorithm used for CMIS, requirements associated with the algorithm, retrieval performance and its dependence on sensor and environmental factors.

2.2. Document Scope

A substantial portion of the process for obtaining the Pressure Profile EDR is performed by the Core Physical Inversion Module, which is described in the *CMIS EDR ATBD Vol 2: Core Physical Inversion Module* (AER, 2000). The material covered in that ATBD is not repeated here. This document describes how the products of the core module are integrated with other algorithms to produce Pressure Profile EDRs.

The ATBD provides outlines for continued algorithm development and advancement and for pre- and post-launch calibration/validation efforts. These outlines are intended to be reviewed and revised prior to launch as new data sources and research become available.

3. Overview and Background Information

3.1. Objectives of the Pressure Profile EDR retrieval

The Pressure Profile algorithm must produce estimates of the atmospheric pressure. The pressure reports are to be made along vertical paths through the atmosphere, using the term profile to refer to a set of pressures along a single path. Each report consists of pressures given as a function of altitude above the surface, for a specified location. Pressure profiles are to be produced within the swath observed by CMIS so that coverage is global upon a series of NPOESS orbits.

For a conical scanner such as CMIS, the paths over which the instrument views the atmosphere are slanted with respect to the local vertical of the observed location. The Pressure Profile algorithm may be configured to produce estimates of pressures along the CMIS view paths, given as a function of altitude. The baseline algorithm, however, produces pressure profiles registered to vertically-oriented paths, for compliance with the CMIS System Requirements Document (SRD).

3.2. Summary of EDR requirements

3.2.1. SRD Requirements

The text below and Table 3-1 are the portions of CMIS SRD section 3.2.1.1.1.1 that apply directly to the Pressure Profile algorithm.

Pressure Profile

A pressure profile is a set of estimates of the atmospheric pressure at specified altitudes above the Earth's surface. The requirements below apply under both clear and cloudy conditions.

Table 3-1: SRD Requirements for the Pressure Profile EDR

Para. No.		Thresholds	Objectives
C40.3.5-1	a. Horizontal Cell Size	25 km	5 km
C40.3.5-2	b. Horizontal Reporting Interval	25 km	5 km
C40.3.5-3	c. Vertical Cell Size	1 km	0 km
	d. Vertical Reporting Interval		
C40.3.5-4	1. 0 - 2 km	1 km	0.25 km
C40.3.5-5	2. 2 - 5 km	1 km	0.5 km
C40.3.5-6	3. > 5 km	1 km	1 km
C40.3.5-7	e. Horizontal Coverage	Global	Global
C40.3.5-8	f. Vertical Coverage	0 - 30 km	0 - 30 km
C40.3.5-9	g. Measurement Range	10 - 1050 mb	10 - 1050 mb
	h. Measurement Accuracy		
C40.3.5-11	1. 0 - 10 km	5 % (TBR)	3 % (TBR)
C40.3.5-12	2. 10 - 30 km	10 % (TBR)	5 %
C40.3.5-13	i. Measurement Precision	4 mb	2 mb
C40.3.5-14	j. Mapping Uncertainty	7 km	1 km
C40.3.5-15	k. Swath Width	1700 km (TBR)	(TBD)

In addition to these requirements, the SRD specifies:

1. "Science algorithms shall process CMIS data, and other data as required, to provide the [EDRs] assigned to CMIS." (SRD, paragraph SRDC3.1.4.2-1)
2. "As a minimum, the EDR requirements shall be satisfied at the threshold level." (SRDC3.2.1.1.1-3)
3. "… the contractor shall identify the requirements which are not fully satisfied, and specify the conditions when they will not be satisfied." (SRCD3.2.1.1.1-4)
4. "… CMIS shall satisfy the EDR Thresholds associated with cloudy conditions under all measurement conditions …" (SRDC3.2.1.1.1.1-1)

3.2.2. Interpretation of SRD requirements

Vertical cell size requirements are used in the SRD to specify depths over which EDR data are vertically averaged for validation. For some EDRs, EDR errors are significantly reduced when vertical averages are considered, as errors at individual levels partly offset each other in the averaging process. A vertical cell size requirement is included among the Pressure Profile EDR requirements. As discussed later in this document, the pressure profile is derived from a process of vertical integration to the reporting levels. The pressure at a given reporting level is directly related to the average temperature of the atmosphere between that level and the surface. When vertical integration is the fundamental process in determining the EDR, vertical averaging of EDR data in the validation process is superfluous. We therefore did not include any averaging over vertical cells in our Pressure Profile EDR performance evaluation, which is equivalent to using a vertical cell size of zero. We consider the vertical cell size requirement to be not applicable.

3.2.3. Requirements imposed by other EDR algorithms

None.

3.3. Historical and background perspective of proposed algorithm

Algorithms for passive sounding from satellites have generally treated pressure as the independent variable of the profile, while retrieving temperature and constituent profiles as a function of pressure (Chahine,1968; Smith, 1970; Hayden, 1988). The surface pressure has generally been provided from external data, such as numerical weather prediction model output or an analysis of surface observations.

3.4. Physics of atmospheric pressure profiling

The brightness temperature, R_ν, at a given frequency ν is computed using the Rayleigh-Jeans approximation as

$$R_\nu \cong \varepsilon_\nu \Theta_s \mathrm{T}_{s,\nu} + \int_{p_s}^{0} \Theta(p) \frac{\partial \mathrm{T}_\nu(p,\theta_u)}{\partial p} dp + (1-\varepsilon_\nu)\mathrm{T}_{s,\nu}\left[\int_{0}^{p_s} \Theta(p) \frac{\partial \mathrm{T}^*_\nu(p,\theta_d)}{\partial p} dp + \mathrm{T}^*_\nu(0,\theta_d)\Theta_c\right]$$

where $\theta(p)$ is the atmospheric temperature at pressure p, $T_\nu(p,\theta_u)$ is the total transmittance due to molecular species and cloud liquid water from pressure p to space at the satellite viewing angle θ_u, $\mathrm{T}^*_\nu(p,\theta_d)$ is the transmittance from surface to pressure p at computational angle θ_d, ε_ν is the surface emissivity, and Θ_c is the cosmic radiation term (Θ_c=2.73 K). It is convenient to use the pressure as the independent variable in the integration because the pressure is the mass of air per unit area and the mass is closely related radiative transmittance. The surface pressure p_s is one of the bounds of integration and can, in principle, be retrieved from the brightness temperatures; however, the sensitivity of microwave brightness temperatures to changes in surface pressure are small enough that surface pressure retrieval is not feasible.

In the Earth atmosphere there is a near balance between the force of gravity and the force of the vertical pressure gradient. This balance is represented by the hydrostatic equation

$$\frac{dp}{dz} = -\rho g$$

where z is altitude, ρ is the air density and g is the acceleration of gravity (Wallace and Hobbs, 1977). This equation can also be written in terms of temperature as

$$\frac{dz}{d\ln p} = -\frac{R_d \Theta_v}{g}$$

where the virtual temperature is $\Theta_v = \Theta(1+0.61q)$, q is the water vapor mixing ratio, and R_d is the gas constant for dry air. Upon integration we obtain the hypsometric equation that can be used to obtain the altitude (above the surface) of a given pressure level:

$$z_i - z_s = -R_d \int_{p_s}^{p_i} \frac{\Theta_v}{g} d\ln p \qquad \text{X}$$

The profile of altitude with respect to pressure is thus a function of the temperature and water vapor profiles. This result can also be viewed as a profile of pressure as a function of altitude.

Equation X has been written for the case where the surface is the reference point where pressure and altitude are given. The integration can also be performed from any other reference level where an estimate of pressure and altitude are available.

3.5. Instrument Characteristics

3.5.1. Channel set

Pressure profile retrieval requires channels for retrieving the temperature and water vapor profiles. The primary CMIS channels for retrieving the temperature profile are the ones in the 50–60 GHz range. The primary water vapor channels are at 23, 166, and 183 GHz. There is a secondary dependence on CMIS channels at 19, 37, and 89 GHz to provide information on surface characteristics and cloud water that may affect radiative transfer in these bands.

Sensor sample processing described in the *Footprint Matching and Interpolation ATBD* (*ATBD Vol. 1, Part 2*) creates composite measurements that are the spatial weighted superpositions of a contiguous group of sensor samples. The process is designed to match observations from different channels to a single reference footprint. The composite fields-of-view (CFOVs) from different channels are more closely matched and collocated than the corresponding EFOVs. In addition, because sensor noise (as measured in NEDT) is both random and independent between samples, the effective NEDT of composite footprints may be reduced if the square-root of the sum of squared sample weights is less than one. The Pressure Profile algorithm uses data processed to match 25×25-km CFOVs.

3.5.2. Derived requirements on sensor data

None.

3.6. Requirements for cross sensor data (NPOESS or other sensors)

The pressure profile algorithm does not require any data from sensors other than CMIS.

3.7. Derived requirements on data from other EDR algorithms

The Pressure Profile algorithm requires surface pressure and view-path temperature and water vapor profile data from the core module with the characteristics specified in Table 3-2. The algorithm also uses view-path water vapor profile data from the core module, for vertical registration, but places no practical requirement on its measurement uncertainty.

Table 3-2: Data requirements placed on the Core Module by the Pressure Profile algorithm

Parameter	Requirement
a. Horizontal spatial resolution	27 km
b. Horizontal reporting interval	13 km
c. Vertical reporting interval	
1. Surface to 100 mb	80 mb
2. 100 mb to 30 mb	15 mb
3. 30 mb to 10 mb	5 mb
d. Horizontal coverage	Global
e. Vertical coverage	Surface to 10 mb
f. Measurement range	
1. Temperature	180-335K
2. Water vapor mixing ratio	0-30 g/kg
g. Measurement Accuracy	
1. Temperature surface to 10 km	1 K average over entire

Parameter	Requirement
	layer
2. Temperature 10 km to 30 km	1 K average over entire layer
3. Water vapor mixing ratio	1 g/kg / 3-km layer
h. Measurement Precision	
1. Temperature	0.82 K / 3-km layer
2. Water vapor mixing ratio	2 g/kg / 3-km layer
i. Measurement Uncertainty for Surface Pressure	2.6 mb
i. Mapping Uncertainty	7 km
j. Swath Width	1700 km (TBR)

3.8. Requirements for ancillary data

None. (See EN #12 response.)

4. Algorithm Description

4.1. Theoretical Description of Algorithm

The Pressure Profile algorithm determines the pressure profile by diagnosis rather than by direct retrieval. The hyposmetric equation (X) is the diagnostic equation, and it operates on the surface pressure and the temperature and water vapor profiles produced by the core inversion module.

The hyposometric equation, in a strict sense, applies to a vertical column of the atmosphere, whereas the core module produces retrievals along the slant path of the CMIS view. Prior to applying the hypsometric equation, the algorithm takes the slant-path temperature and water vapor profiles and performs an interpolation process to register the profile data into alignment with the local vertical. The vertical registration process is illustrated in Figure 4-1 for the case of temperature interpolation. The process excludes any core module data flagged as being unreliable, such as due to precipitation.

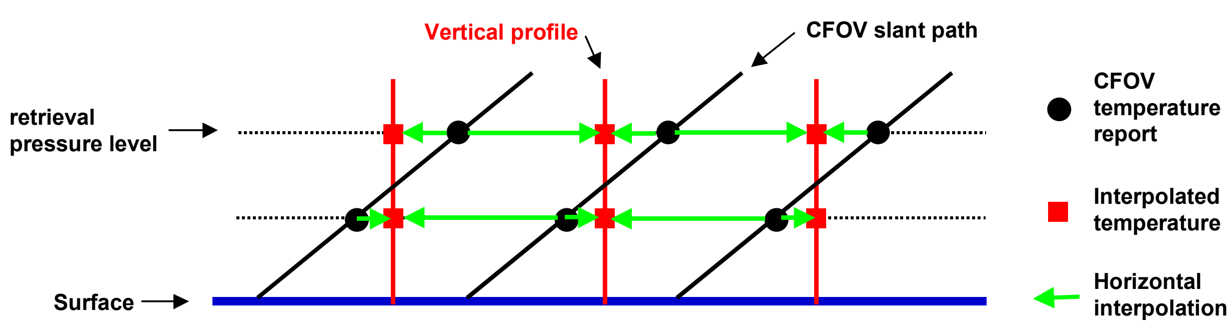

Figure 4-1. Illustration of the process of vertical registration of the temperature profile, for a cross-sectional view through a portion of a scan.

To compute the horizontal locations of the slant path data at a given retrieval pressure level it is necessary to know the altitude of the pressure level so that parallax can be accounted for. The horizontal displacement from the location at the surface is $(z_i - z_s)\tan\zeta$, where ζ is the zenith angle (Earth incidence angle).

The basic procedure of the algorithm is:
1) compute altitudes of retrieval levels on slant paths,
2) compute horizontal locations of data at each retrieval level,
3) horizontally interpolate retrieval data to vertical paths,
4) compute altitudes of retrieval pressure levels on vertical paths, and
5) vertically interpolate to obtain pressures at reporting altitudes.

The catch is that, in order to compute the altitudes of the vertical profiles we need to already have the altitudes on the slant paths, but the hypsometric equation does not strictly apply to slant paths. One option would be to iterate through the procedure, but that is not necessary. The atmosphere is smooth enough that the horizontal interpolations are not sensitive to the relatively small location errors that arise from using slant-path data to compute the initial altitudes. For example, even a 5% error in the slant-path altitude would introduce only a 2 km location error at 30 km altitude, which is small in relation to the 25-km cell size for this EDR.

4.2. Mathematical Description of Algorithm

4.2.1. Profile retrieval

The hypsometric equation is solved in a discrete form, as

$$\Delta z_i = \frac{\Theta_{vi} + \Theta_{vi+1}}{2} \frac{R_d}{g_{i+1}} \ln\left(\frac{p_{i+1}}{p_i}\right), \quad z_i = \sum_{i=N-1}^{1} \Delta z_i, \quad z_N = z_s,$$

where the index *i* corresponds to one of the core module retrieval levels. The gravitational acceleration *g* is computed from $g_i = GM_e/(R_e + z_i)^2$, where *G* is the gravitational constant, M_e and R_e are the mass and radius of the Earth, respectively.

The vertical interpolation is done in terms of the logarithm of pressure as

$$p_k = \exp\{[\ln(p_{i+1})(z_i - z_k) + \ln(p_i)(z_k - z_{i+1})]/(z_i - z_{i+1})\},$$

where *k* is a reporting level.

4.2.2. Vertical registration

The main process for vertical registration consists of horizontal interpolation from the locations of slant path data to the locations of the reporting grid. Details of the interpolation method are given in the *CMIS ATBD Volume 1: Overview, Part 3: Gridding*.

4.3. Algorithm Processing Flow

4.3.1. Processing Flow for CMIS Pressure Profile Algorithm

The processing flow for the Core Module is illustrated in the *ATBD for the Core Physical Inversion Module* (*ATBD Vol. 2*; AER, 2000). The process for vertical registration of the profile data is illustrated in Figure 4-2. The process for deriving the Pressure Profile EDR is illustrated in Figure 4-3.

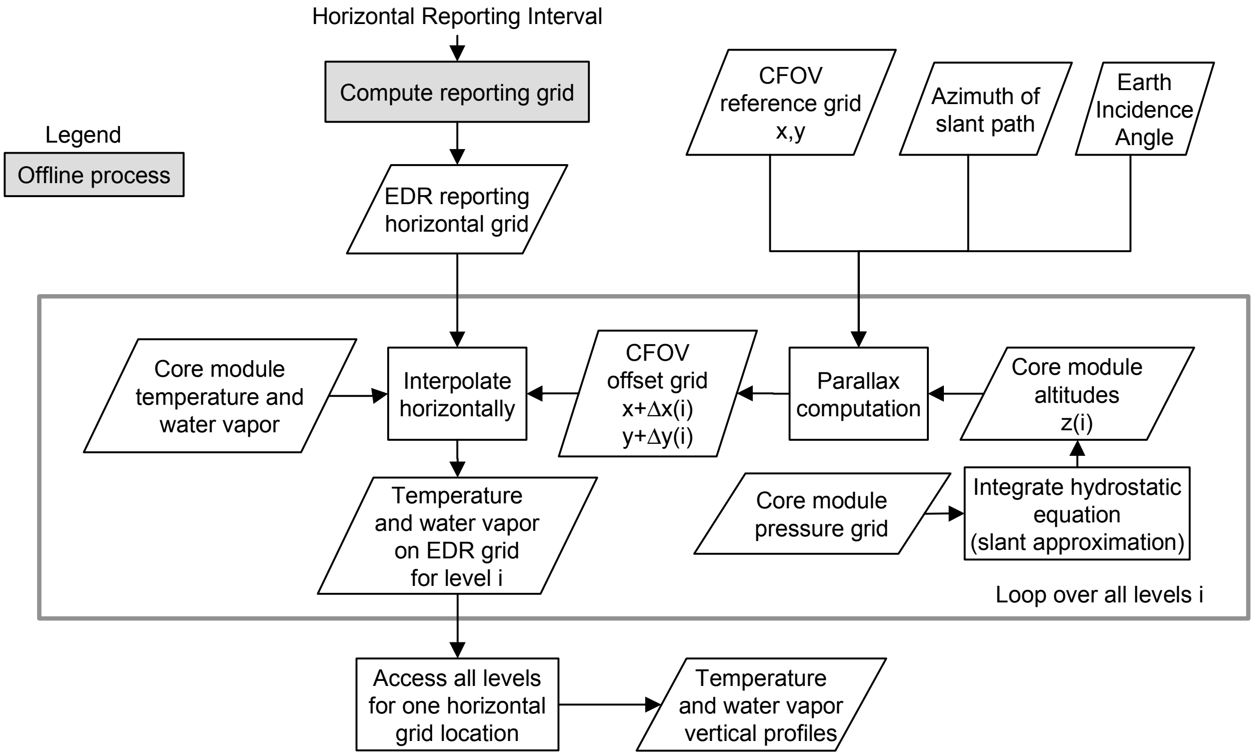

Figure 4-2. Processing flow for vertical registration for the Pressure Profile EDR algorithm.

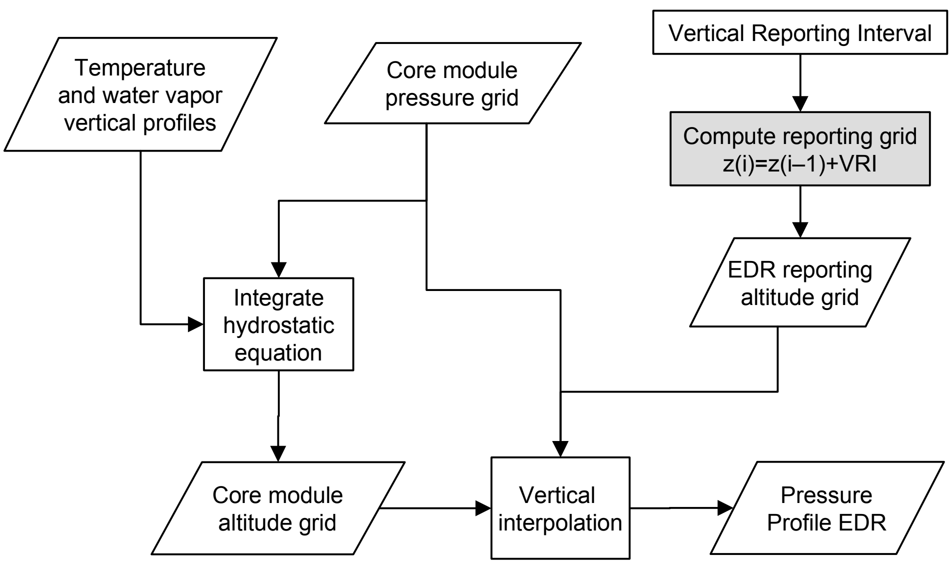

Figure 4-3. Processing flow for the Pressure Profile EDR

4.3.2. Relationship to Overall CMIS Processing Flow

The front end of the EDR algorithm set is the footprint matching algorithm, which is described in the *Footprint Matching and Interpolation ATBD* (*ATBD Vol. 1, Part 2*). That algorithm provides the brightness temperatures to the core inversion module. The baseline CFOV size for pressure profile processing is 25×25 km^2. The Pressure Profile EDR algorithm is a postprocessor on the core inversion module.

4.4. Algorithm inputs

Table 4-1. Pressure Profile algorithm inputs

Data	Type	Source	Usage
Latitude/longitude at surface	"	SDR	EDR reporting
Time/date	"	SDR	"
Slant-path temperature profiles	Dynamic, periodic	Core Module	Vertical registration and EDR production
Slant-path water vapor profiles	"	Core Module	Vertical registration and EDR production
Surface pressure	"	Core Module	EDR production
Surface altitude	"	Core Module	Vertical registration and EDR production
CFOV identifier indices	"	Core Module	Vertical registration
CFOV reference grid	Static	Scan description database	"
Azimuth of slant path in scan coordinates	"	Scan description database	"
Horizontal reporting grid	"	Specifications database	"
Vertical reporting grid	"	Specifications database	Vertical interpolation

4.5. Algorithm outputs

Table 4-2. Pressure Profile algorithm outputs

Output parameter
Pressure profile
Latitude/longitude at surface
Time/date
CFOV identifier indices
Quality flag

4.6. Timing benchmark

The computation time for the vertical integration and interpolation portions of the Pressure Profile EDR processing are negligible in relation to the computation time for the core module. The processing time for the horizontal interpolation (vertical registration) is TBD, but is not expected to be a driver on computational requirements.

5. Algorithm Performance

The fundamental steps of performance testing are:

1) select test cases, with description of all relevant environmental parameters,

2) simulate CMIS brightness temperatures, accounting for sensor design parameters and error characteristics,
3) perform EDR retrievals, and
4) compare retrieved EDRs to the “true” EDRs, which are derived directly from the test case data.

5.1. Performance test conditions

The primary test cases are described here briefly and, more extensively, in the *ATBD for the Core Physical Inversion Module* (*ATBD Vol. 2*). The atmospheric temperature and water vapor profiles and the surface temperatures were derived from the NOAA-88 database. Liquid clouds were simulated by assuming uniformly-distributed cloud liquid water over a layer whose bounds varied randomly from profile to profile. The total cloud liquid water varied randomly from 0 to 0.5 kg/m^2. Oceanic profiles were paired with emissivity spectra from the Kohn/Wilheit model. Warm land profiles (surface skin temperature > 273 K) were paired with land emissivity spectra derived from the Prigent database. Cold land profiles (surface skin temperature < 273 K) were paired with snow/ice emissivity spectra also derived from the Prigent database.

5.2. Performance overview

Retrieval performance is shown in Figure 5-1. These results were obtained from a set of 1000 cloudy land profiles from the NOAA-88 dataset. The errors in terms of absolute standard deviation (measurement precision) are dominated by the error in the surface pressure, which was simulated as 2.5 mb. The same surface pressure error was assumed under clear and cloudy conditions and all surface types, so the pressure errors are not sensitive to these aspects of the sensing environment. Cloudy land cases are the most stressing, so performance is shown for that case. The biases in the simulated retrievals are very small in relation to the requirements because systematic calibration errors (brightness temperature biases) were not included in these simulations and because the core algorithm introduces very little systematic error in the layer-average temperature and water vapor retrievals.

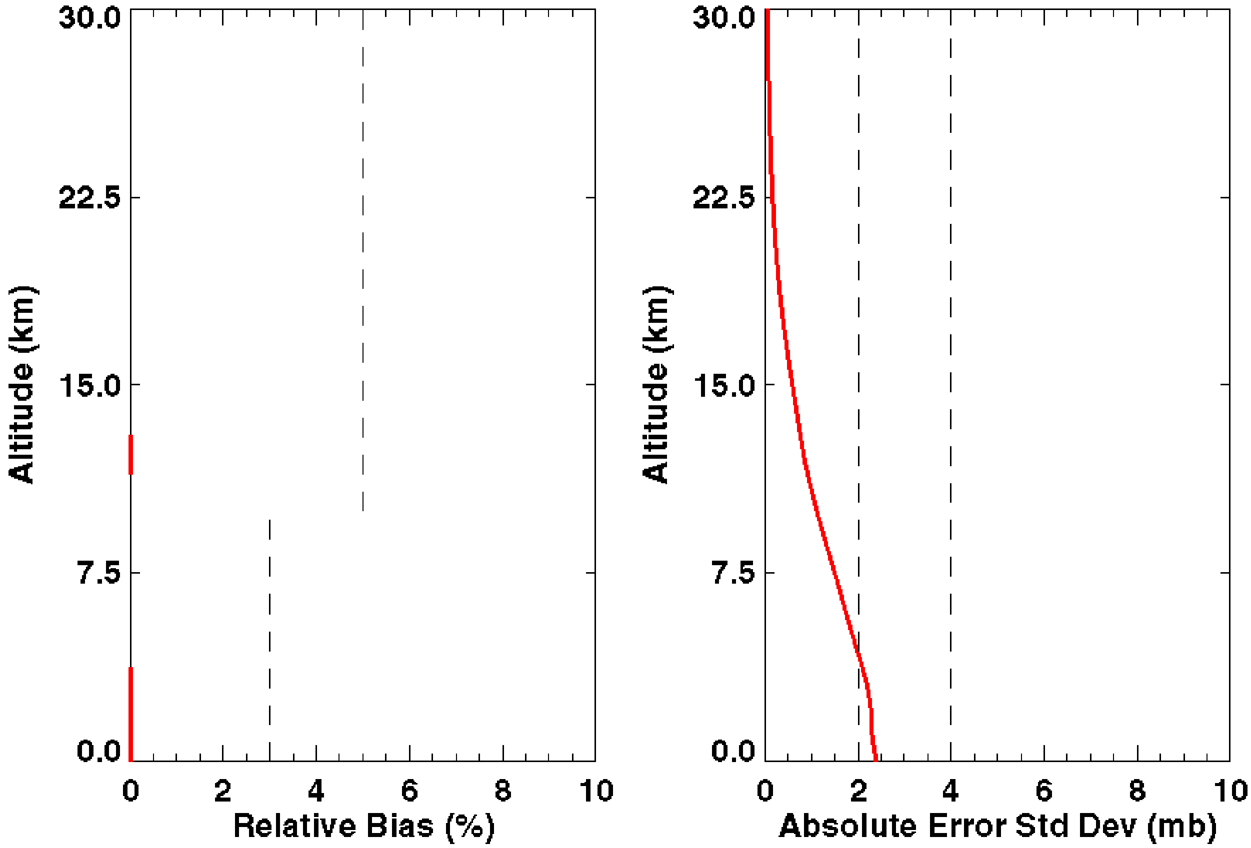

Figure 5-1. Pressure profile retrieval rms error for land surfaces and cloudy atmospheres. The dashed lines are the SRD objectives for measurement accuracy in the bias plot and the SRD threshold (4 mb) and objective (2 mb) for measurement precision in the standard deviation plot.

5.3. Performance summary

The Pressure Profile EDR error budget is in Table 5-1. Terms listed with zero error indicate that the error term is considered to be negligible, and not that the error will be identically zero. The term identified as "core module retrieval (simulated)" includes all terms covered by the simulations, including sensor data noise, retrieval errors and 2.5 mb surface pressure error. The core module requires 2.5 mb uncertainty in the external surface pressure data it receives. Under the heading "core module retrieval (unsimulated)", an additional 0.1 mb uncertainty is budgeted for terrain correction errors and 0.3 mb uncertainty is budgeted for all other potential sources of random retrieval error. The requirements for core module input data (Table 3-2) reflect these additional errors. The measurement precision requirements on temperature and water vapor were derived from the 0.3 mb allocation by considering a case with a surface pressure error of 2.5 mb and finding the layer virtual temperature error that would cause pressure profile error to increase from the surface value to a maximum of 2.8 mb (2.5+0.3 mb). With virtual temperature errors at that magnitude, the maximum pressure error occurs about 3 km above the surface.

The errors associated with vertical registration arise in the computation of the altitudes of the retrieval levels and in the horizontal interpolation to the reporting grid. The amount allocated is more than would be expected in ordinary conditions. For measurement accuracy, it is vastly more than would be expected. The large accuracy allocation fits within the SRD objectives and allows for errors of interpolation over long distances across precipitating areas.

Cell mismatch error refers to the difference between the spatial sampling pattern of the CFOV and the uniformly weighted square over which validation data are to be average. This error is estimated to be negligible because a large portion of the energy in the channels used for this EDR comes from within a 25×25-km square area (*see ATBD Vol. 1, Part 2, Footprint Matching and Interpolation*) and because atmospheric dynamics dictate that pressure fields are smooth on the 25-km scale over the vast majority of the Earth.

The net error is computed as the root sum of squares of the individual terms, under the assumption that the terms are statistically independent of each other.

Table 5-1. Pressure Profile EDR Error Budget.

Term	**Measurement Accuracy**		**Measurement Precision**
	0 km to 10 km	10 km to 30 km	
Core module retrieval (simulated)	0.1 %	0.1 %	2.5 mb
Core module retrieval (unsimulated) terrain correction	0 %	0 %	0.1 mb
Core module retrieval (unsimulated) other random errors	0 %	0 %	0.3 mb
Core module retrieval (unsimulated) brightness temperature bias	0.5 %	1.5 %	0 mb
Vertical interpolation	0 %	0 %	0 mb
Vertical registration (horizontal interpolation)	2.9 %	4.7 %	1.6 mb
Cell mismatch	0 %	0 %	0 mb
Net error	**3 %**	**5 %**	**3 mb**

5.4. Performance under degraded measurement conditions

The measurement accuracy allocations for vertical registration under nominal conditions correspond to biases in virtual temperature of about 6 K for the layer 0 to 10 km and 1.6 K for the layer 10 to 30 km. It would be very rare to have errors larger than this magnitude even for interpolation across precipitation, so no adjustment to the measurement accuracy requirements is needed to accommodate precipitation. For virtual temperature interpolation errors of 5 K (standard deviation) due to precipitation, the measurement precision errors increase by about 5 mb from the surface value (with a maximum near 400 mb), so a measurement precision of 8 mb can be met under precipitating conditions.

If surface pressure data do not meet the input data requirements, the pressure profile EDR measurement precision performance will be degraded an amount approximately equal to the degree to which the input surface pressure data exceed thresholds. The measurement accuracy requirement would be unaffected because the climatological standard deviation of surface pressure is less than 3%.

6. Algorithm Calibration and Validation Requirements

6.1. Pre-launch

6.2. Post-launch

6.3. Special considerations for Cal/Val

6.3.1. Measurement hardware

6.3.2. Field measurements or sensors

6.3.3. Sources of truth data

Routine radiosondes provide sufficient accuracy to validate the Pressure Profile EDR. Validation of horizontal cell averages would require a network of closely spaced radiosondes.

7. Practical Considerations

7.1. Numerical Computation Considerations

7.2. Programming/Procedure Considerations

7.3. Computer hardware or software requirements

7.4. Quality Control and Diagnostics

7.5. Exception and Error Handling

7.6. Special database considerations

7.7. Special operator training requirements

7.8. Archival requirements

8. Glossary of Acronyms

ATBD	Algorithm Theoretical Basis Document
CFOV	Composite Field Of View
CMIS	Conical Microwave Imaging Sounder
EDR	Environmental Data Record
EIA	Earth Incidence Angle
NPOESS	National Polar-orbiting Operational Environmental satellite System
RMS	Root Mean Square
SDR	Sensor Data Record

9. References

9.1. Technical Literature

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